

Journal of Rehabilitation Research and Development

Rehabilitation R & D Progress Reports 1990

VIII. Muscles, Ligaments, and Tendons

A. Muscles

B. Ligaments and Tendons

VIII. Muscles, Ligaments, and Tendons

For additional information on topics related to this category see the following Progress Reports: [122], [344], [567].

A. Muscles

[284] Noninvasive Electromyography

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Sponsor: VA Rehabilitation Research and Development Service (Project #B496-RA)

Purpose—Clinical electromyographic (EMG) signals are currently recorded using intramuscular needle electrodes. Noninvasive surface electrodes would be less painful and more easily accepted by many patients, especially children. However, since EMG signals are attenuated and distorted by the subcutaneous tissues and skin, surface EMG recordings have been considered unsuitable for electrodiagnosis. Recently, new electrodes have been developed to overcome some of this distortion. They consist of an array of small surface contacts whose outputs are combined via a spatial filter. We are interested in optimizing the design of these electrode arrays and in developing methods to analyze the signals they record.

Progress/Methodology—In order to investigate the influence of the size and shape of the surface electrode on the electrical properties of the recorded signal, we measured the electrical impedance of electrodes ranging in size from 0.02 to 0.125 inches in diameter and having

cylindrical, hemispherical, and conical shapes. Each electrode was pressed against the skin over the abductor pollicis brevis or the brachial biceps with a constant force (50 g). The skin had been rubbed with an alcohol wipe. The impedance between the test electrode and a large ground electrode on the forearm was measured as a function of frequency from 10 to 1,000 Hz.

Results—Impedance decreased with frequency for all electrodes. As a function of size, impedance was less for the larger electrodes, because of increased contact area, and for the smaller electrodes, because of increased contact pressure. Conical electrodes had lower impedances than cylindrical and hemispherical ones at low frequencies (1 versus 10 megohms at 10 Hz, 0.125 in diameter), but roughly the same impedances at high frequencies (0.1 megohms at 1,000 Hz). We conclude that small electrodes with tips sharp enough to indent but not pierce the skin have sufficiently low impedances to be practical for surface recording.

[285] Muscle Fiber Recruitment During Submaximal Electrical Stimulation

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Sponsor: VA Rehabilitation Research and Development Service (Project #B591-RA2)

Purpose—The purpose of this project was to determine the distribution of muscle fibers activated using transcutaneous electrical muscle stimulation (EMS).

Results—This study was based on the observation that, in spite of the relatively low torque levels achieved with 50 Hz EMS (average torque = 15.2% \pm 16.8% of maximum

voluntary contraction levels; mean \pm standard deviation, $n=40$ subjects), all subjects complained of muscle soreness which is not associated with 15% voluntary contractions. We hypothesized that either a superficial "shell" of fibers was activated, or perhaps a certain fiber type was preferentially activated. In a rabbit neuromuscular model, we repetitively activated the tibialis anterior (TA) to (initially) about 20% maximum tension for approximately one hour. After about one hour, force had dropped to an average of 1.3% of maximum. Muscles were then rapidly frozen and stained for fiber type, and active fibers identified using the glycogen depletion method. The distribution of fiber types present in the sample area was: $45 \pm 4\%$ FG, $42 \pm 5\%$ FOG, and $13 \pm 4\%$ SO fibers. However, the distribution of fiber

types depleted (i.e., activated) in the sample area was: $73 \pm 6\%$ FG, $18 \pm 5\%$ FOG, and $9 \pm 6\%$ SO fibers. In all cases, there was a significant difference between activated fibers and fibers present.

Implications—These data suggest that neural stimulation via a cuff electrode can preferentially activate a specific fiber type.

Recent Publications Resulting from This Research

Human Quadriceps Muscle Fatigue at Three Frequencies and Two Duty Cycles Through the Utilization of Functional Electrical Stimulation. Robison MJ, Lieber RL, in Proceedings of Cumberland College 7th Conference on Motor Disturbances, 7:45, 1989.

[286] Biochemical and Myoelectric Events During Fatigue

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Sponsor: VA Rehabilitation Research and Development Service (Project #B593-RA, Part 1); Boston University Medical Center

Purpose—This project is designed to gain more detailed understanding of how biochemical changes associated with fatigue influence the behavior of the median frequency and conduction velocity estimates of the electromyographic (EMG) signal. Neuromuscular strip preparations from the hamster diaphragm were studied *in vitro*. A specialized array of surface EMG electrodes was designed and developed for monitoring EMG signal spectral parameters and conduction velocity from electrically elicited contractions. The diaphragm muscle strip was instrumented to record its contractile tension. The experimental setup provided a unique opportunity to directly control the biochemical conditions of the muscle environment and record this effect on the electrophysiology and contractile state of the muscle.

Progress—We conducted two studies this year. One series of investigations was recently completed to establish a causal relationship between muscle pH and the EMG signal. Muscle pH (or $[H^+]$) is believed to play a key role in muscle fatigue and the concurrent changes in the EMG signal. A series of sustained contractions were electrically elicited at varying bath pHs in a total of eight preparations. The results indicate that the initial median frequency and initial conduction velocity changed by equal percentages as a function of bath pH. This finding implies that the

change in conduction velocity causes a compression (or expansion) of the M-wave rather than a change in its fundamental shape. In contrast, during sustained muscle contractions, median frequency changed by a greater percentage than conduction velocity. This observation implies that, in addition to the changes due to conduction velocity and pH, there is a change in the fundamental shape of the M-wave involving a physiological process other than pH.

Preliminary Results/Future Plans—A second series of investigations to study the effects of compensated (buffered) and uncompensated acidosis on diaphragm function and EMG parameters was conducted on an additional 12 preparations. Although the data have not been completely analyzed, preliminary results indicate that these conditions have a significant effect on the EMG signal and force. We have observed that compensated acidosis actually improves the muscle's ability to generate force during the short duration of the contraction. Further analysis is planned to correlate the EMG signal and force behavior for both studies.

Recent Publications Resulting from This Research

Biochemical and Myoelectric Events During Fatigue. DeLuca CJ et al., presented at the 19th Annual Meeting of the Society for Neuroscience, Phoenix, 1989.

[286a] Low Back Pain and Muscle Fatigue

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Sponsor: VA Rehabilitation Research and Development Service (Project #B593-RA, Part 2); Liberty Mutual Insurance Company

Purpose—As many as 75 million Americans now suffer from severe low back pain and each year 7 million more people develop this problem. Despite the many millions of dollars spent on innumerable treatments for the back, the majority of patients have chronic, recurring symptoms. Improved methods for assessing back disorders could help to diminish the prevalence and the financial burden of this disabling condition. We have developed and are implementing a technique to provide the clinician with an objective index with which to measure treatment outcome for lower back musculature. This technique estimates the fatigue rate of contracting muscles by surface-detected EMG signals. The dynamic interaction of synergistic back muscles during fatiguing contractions may be represented by “fatigue patterns” created by the frequency shifts in various muscles. Differences in these patterns associated with low back disorders may represent functional disturbances in back muscles.

Methodology—The EMG measurement technique for the lower back was recently redesigned to meet the needs of the clinical environment where it is presently used as a research instrument. This technique, called the Back Analysis System (BAS), is described in Part 3 of this report. Our goal is to develop a database large enough for future diagnostic capabilities. Numerous tests are being conducted at several clinical sites using a standardized protocol that includes both high and low force levels of contraction. A brief contraction is repeated one minute following these tests to measure the recovery process from fatigue of lower back muscles.

Progress/Preliminary Results—Our assessment technique targets specific subcategories of low back pain. For example, we are testing patients with at least a 6-month history of chronic back pain but no radiographic evidence of spinal abnormalities. Unlike our previous pilot studies, we are including more aged and female subjects in these tests. We have also begun testing patients with structural spinal disorders in the subacute and chronic stages of low back pain. An activity-level survey and pain questionnaire have been included in the standard protocol. Conventional measures of spinal mobility and static strength have been obtained and compared to EMG median frequency measurements. Our results to date indicate that the EMG parameters are able to discriminate low back pain patients from pain-free control subjects, whereas conventional methods are not.

Recent Publications Resulting from This Research

Lumbar Muscle Fatigue and Chronic Lower Back Pain.

Roy SH, DeLuca CJ, Casavant DA, Spine 14(9):992-1001, 1989.

Lumbar Muscle Fatigue and Chronic Lower Back Pain. Roy SH, DeLuca CJ, Casavant DA, presented at the Annual Combined Sections Meeting of the APTA, Honolulu, 1989.

Lumbar Muscle Fatigue and Chronic Lower Back Pain. Roy SH, DeLuca CJ, Casavant DA, presented at the Italian/American Medical Conference, Bologna, Italy; the 20th International Symposium on Rehabilitation Research of the Handicapped and the Developmentally Disabled, Cairo, Egypt; the 21st International Conference on Rehabilitation and Developmental Disabilities, Milan, Italy, 1989.

[286b] Back Analysis System (BAS)

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Sponsor: VA Rehabilitation Research and Development Service (Project #B593-RA, Part 3); Liberty Mutual Insurance Company

Purpose—During the past 3 years, we have continuously refined our methods used to evaluate muscle performance in individuals with and without low back pain. A key component in these investigations has been the Back

Analysis System (BAS), a computerized EMG spectral analysis system coupled to a pelvic restraining device.

The BAS and its associated apparatus is designed to stabilize and isolate the trunk musculature and analyze

the patterns of muscle activity observed during isometric contraction of the back muscles. The specialized restraint apparatus is designed to immobilize the pelvis and assure that the contribution to the flexion and extension forces is limited to the muscles of the lower back. The system configuration and experimental protocols which may be selected via software permit researchers to tailor the BAS to a variety of back performance evaluations.

Progress—Over 200 individuals have been evaluated using the BAS, generating a research database consisting

of “normals,” athletes, and individuals with muscular dysfunction such as fibromyalgia. To augment this database and expand the application of the System to clinical settings, a BAS has been placed at Boston City Hospital as part of a collaborative project with their Department of Orthopedics.

This system was demonstrated for the VA Congressional Subcommittee on Hospitals and Health Care in Washington, DC, in September 1989.

[286c] Back Assessment of Athletes from Varsity and Freshman Crew Teams

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Sponsor: VA Rehabilitation Research and Development Service (Project #B593-RA, Part 4); Liberty Mutual Insurance Company

Purpose—The purpose of this study is to determine whether correct identification of low back pain can be accomplished in a mixed population of novice and experienced freshman rowers based on EMG spectral parameters from lumbar muscles. By repeating the BAS test procedures twice a year until the novice rowers complete their varsity year, we will be able to validate the technique further as a screening device for low back pain. The effects of athletic training and exercise on EMG parameters of the lower back will also be assessed.

Progress—Twenty-five members of the Boston University men's freshman crew team have participated in this study to date. As new freshman crew members join the team, they will be recruited for the study.

Preliminary Results/Implications—In the fall 1988 rowing season, we completed the preliminary phase of

testing. The results from this part of the study indicated that EMG signal spectral analysis can correctly identify rowers with low back pain from a mixed population of novice and experienced freshman rowers. The crew team was retested in the spring, following a winter training period. The preliminary results show an increase in static strength of back extensors and an improvement in fatigability for the novice rowers, but not for the experienced rowers. However, novice rowers after one year of training did not achieve the same level of maximal voluntary contraction or resistance to fatigue as the more experienced rowers. These findings indicate that extensive training can modify the frequency spectrum of the EMG signal. We hope that our data and analysis will be useful to the individual athletes and their coach as an objective measure for designing and assessing training procedures.

[286d] Back Assessment in Patients with Fibromyalgia

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Sponsor: *VA Rehabilitation Research and Development Service (Project #B593-RA, Part 5); National Institutes of Health; Liberty Mutual Insurance Company*

Purpose—Fibromyalgia, also called fibrositis, is increasingly recognized as one of the most common causes of chronic musculoskeletal pain and fatigue. It is classified within the spectrum of generalized nonarticular rheumatism and affects between three and six million Americans. The most compelling pathophysiologic evidence for objective abnormalities in fibromyalgia has come from recent studies of muscle histology and physiology. These results, although not conclusive, have prompted rheumatologists at the Arthritis Center of The University Hospital to study the muscular component of fibromyalgia via objective fatigue measures developed in our laboratory. This interest follows a number of years of clinical research to help delineate fibromyalgia from other similar disorders.

Preliminary Results—A study was completed in which 10 patients with fibromyalgia and 10 control patients

were tested for muscle function in the lower back. The BAS was used to identify abnormal patterns of fatigue during sustained isometric contractions and recovery. Abnormal muscle fatigue was not present in the lower back muscles of fibromyalgia patients. Conversely, patients with chronic low back pain but no diagnosis of fibromyalgia demonstrated abnormal fatigue at the L2 and L5 lumbar levels in the paraspinal muscles. More comprehensive studies involving lower-limb and shoulder muscles of patients with fibromyalgia are under way.

Recent Publications Resulting from This Research

Back Assessment in Patients with Fibromyalgia. DeLuca CJ et al., presented at the 1st International Symposium on Myofascial Pain and Fibromyalgia, Minneapolis, 1989.

[286e] Mechanical Recruitment of Low Back Muscles

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Sponsor: *VA Rehabilitation Research and Development Service (Project #B593-RA, Part 6); Boston University (Patricia Harris Fellowship)*

Purpose—By assuming that the EMG signal level of a given muscle reflects its force output, a physical task that requires a constant muscle force output level can be designed. If the EMG signal level recorded from that muscle is found to be constant, a relationship between the predicted force level and the measured EMG signal level can be established. Such an experiment presents a new level of testing of the biomechanical model and, if successful, could further strengthen the relationship between mechanical loading and lumbar muscle activation.

Progress—Our biomechanical model of the lower back, developed during the past 3 years, was further studied. The muscle activity surfaces that summarize the muscular

force of each of the 22 different muscles that cross the L3 level were analyzed to identify external loading combinations that require a constant muscular force response. We can therefore predict that a given quasi-static loading exercise involving moving a hand-held weight in front of the body will require a constant force output of a given muscle in the lumbar region. Such an exercise can be described by an isoforce curve in the "loading plane" (a mathematical plane whose axes are the flexion and lateral bending moments). By describing the isoforce curves of a given muscle on the loading plane, a map of the predicted activation levels of that muscle is created. Mathematically, these curves were derived from different lumbar muscles by intersecting the muscle activity surface and a plane representing a constant force level.

Recent Publications Resulting from This Research

Theoretical Predictions and Experimental Validation. Ladin Z, Murthy KR, DeLuca CJ, *Spine* 14(9):927-938, 1989.

Awards

Mechanical Recruitment of Low-Back Muscles. Volvo Award in Biomechanics, 1989.

[286f] The Lumbarator: A Real-Time Simulator of Lumbar Muscle Force Distribution

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Sponsor: VA Rehabilitation Research and Development Service (Project #B593-RA, Part 7)

Purpose—The purpose of this study was to devise a prototype system for the design of weightholding exercises and to study the muscular load-distribution resulting from those exercises.

Results—The prototype system has been completed. The graphic display of the system involves two screens: an exercise-design screen and a muscle-force display screen. The exercise-design screen is composed of four windows that describe the four different views of the human model. The middle window is the load and posture-selection window. Using the mouse, loads for the left and right hands can be selected. By placing the mouse on the angle selection window, a series of points representing elbow angle and shoulder angle can be selected for both hands, representing a complete quasi-static exercise. Based on the elbow angle, shoulder angle, and load in left and right hands for each position in the quasi-static exercise, flexion moment and lateral bending are calculated. The moment combination is used to access the database of the muscle activity surfaces for all 22 muscles, and the individual muscle forces that correspond to that loading condition are calculated.

The muscle-force screen displays in real-time the distribution of muscle forces in the lower back in

response to gravitational loading. Using a precalculated database of muscle activity surfaces for 22 muscles crossing the L3 level in the lumbar region, the system displays the load distribution among all the different muscles using a color or a gray-level scale and, therefore, enables the user to study immediately the effect of given quasi-static exercises on muscle force distribution in all the muscles of the cross-section of interest. The forces are displayed on the right side of the screen using a color or a gray-level scale. By placing the mouse cursor inside the table, the “switching curve” of that particular muscle can be displayed on the “loading plane.” The “switching curve” separates the loading combination that will activate the muscle (on one side of the curve) from those that will not (on the other side of the curve). Thus, using the mouse, quasi-static exercise can be designed which would simulate, in real-time, variations in individual muscle forces.

Recent Publications Resulting from This Research

The Lumbarator: A Real-Time Simulator of Lumbar Muscle Force Distribution. DeLuca CJ, Ladin Z, Guha S, in *Proceedings of the 12th International Congress of Biomechanics*, Los Angeles, 1989.

[287] The Myoelectric Signal Decomposition Technique

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Sponsor: VA Rehabilitation Research and Development Service (Project #B594-RA, Part 1)

Purpose—Myoelectric (ME) signal decomposition is a technique for studying the firing behavior of individual motor units, as well as the interactions of populations of simultaneously active motor units. This technique consists of three main parts: signal detection, acquisi-

tion, and decomposition. Refinements to this technique for analyzing motor unit firing behavior have focused on detecting and acquiring better quality signals and decomposing these signals with greater speed and accuracy.

Progress/Preliminary Results—We continued to implement a number of improvements on the decomposition process. New techniques were developed to graphically display intervals of motor unit activity while our specialized multichannel needle electrode is positioned in the muscle. Also, we experimented with alternative approaches for automatically decomposing ME signals and some new post-decomposition algorithms for monitoring

and displaying the results of our decomposition technique. These analysis routines have facilitated our studies of synchronous motor unit firing, common modulation of motor unit firings, "common drive," macro-electromyography, and the effects of muscular fatigue on motor unit firing behavior. Together with our improvements in data acquisition, these changes have decreased the time required to collect and analyze high quality data.

[287a] Motor Unit Firing Behavior in Older Adults

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Sponsor: VA Rehabilitation Research and Development Service (Project #B594-RA, Part 2); Liberty Mutual Insurance Company

Purpose—The NeuroMuscular Research Center has embarked on a long-term study to determine the changes in neuromuscular and central nervous system function affecting older adults. Our goal is to determine alternative intervention strategies to improve functional status. Toward this end, we have been exploring motor unit firing behavior in the aged. Our experiments indicate that some of the observations made in younger individuals match those seen in the elders. For example, motor unit firing rates tend to be higher in small muscles than in large muscles. However, in some individuals the force at which a motor unit is activated does not match the force

at which it is deactivated. Our current studies involve the relationship among macro-EMG area, axonal conduction velocity, and recruitment threshold in order to determine how the known changes in the morphology of the motor unit affect firing behavior.

Recent Publications Resulting from This Research

Unusual Motor Unit Firing Behavior in Older Adults. Kamen G, DeLuca CJ, *Brain Res* 482(1):136-140, 1989.

Motor Unit Firing Behavior in the Aged. Kamen G, DeLuca CJ, in *Computer-Aided Electromyography and Expert Systems*, 231-239, J.E. Desmedt (Ed.). Amsterdam: Elsevier Science Publishers B.V., 1989.

[287b] Recurrent Inhibition in Older Adults

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NeuroMuscular Research Center, Boston, MA 02215

Sponsor: VA Rehabilitation Research and Development Service (Project #B594-RA, Part 3); Liberty Mutual Insurance Company; Boston University

Purpose—In our effort to improve our understanding of spinal reflex systems in the elderly, we have been studying recurrent inhibition in older adults. Our previous work indicates that under some conditions the integrity of both short- and long-latency reflexes may be improved in older adults. Our working hypothesis is that these changes may indicate that some underlying neural compensation is possible in the spinal reflex center.

Methodology/Progress—To test this idea, we have undertaken a study of an important neural pathway affecting the motoneuron—the recurrent inhibitory system mediated by the Renshaw cell. This neural system is important in a number of motor tasks including those

involving various levels of cocontraction of agonist and antagonist muscles and oscillating activity such as walking. The technique utilized paired conditioning-test electrical stimuli delivered to the tibial nerve during conditions involving various degrees of voluntary effort. Our early experiments have demonstrated satisfactory test-retest reliability and we are preparing to begin comparisons of results from aged and college-age adults.

Recent Publications Resulting from This Research

Recurrent Inhibition in Older Adults. Kamen G et al., presented at the Annual Meeting of the American Academy of Clinical Neurophysiology, Boston, 1989.

[287c] The Role of Cutaneous Receptors in Motor Unit Firing Behavior

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Sponsor: VA Rehabilitation Research and Development Service (Project #B594-RA, Part 4); Liberty Mutual Insurance Company

Purpose—In previous experiments, we demonstrated that desensitizing the skin through the application of a topical anesthetic can have a marked effect on motor unit firing rate and recruitment threshold. This study sought to further investigate the role of cutaneous receptors on motor unit firing behavior through the use of electrical stimulation of cutaneous receptors.

Results/Future Plans—Myoelectric signals were obtained from the first dorsal interosseous muscle while the subject followed a trajectory on a monitor, requiring the production of up to 50% of maximal voluntary

contraction (MVC). These signals were decomposed into constituent motor unit action potential trains, and the recruitment thresholds and maximal firing rates (at 50% MVC) were determined before and after 3 minutes of skin stimulation at an intensity equivalent to three times perceptual threshold. For most motor units, the force at which units were recruited increased while maximal firing rate decreased. However, the effect was less dramatic than that observed by other investigators. We plan to investigate and determine whether skin receptors have similar influence on both tonic and phasic motoneurons.

[288] Characterization of Back Muscles by Means of Electrical Stimulation

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Sponsor: VA Rehabilitation Research and Development Service (Project #B595-RA); National Research Council of Italy; Liberty Mutual Insurance Company

Purpose—The objective of this project is to assess the feasibility of back muscle characterization by means of electrical stimulation techniques. If feasible, the technique would be relevant to our work on low back pain.

Preliminary Results—Thirty-five experiments were performed on 19 healthy male subjects. The longissimus dorsi (LD) and the iliocostalis lumborum (ILC) muscles were individually stimulated at two intensities and two frequencies while myoelectric signals were detected from both muscles. Conduction velocity (CV) and mean and median frequency (MNF and MDF) were estimated. Selective stimulation of a single muscle was not always possible. Partial data analysis shows that out of 42 contractions, 10 showed activation of the LD during stimulation of the ILC and 8 showed activation of the ILC during stimulation of the LD. In 17 contractions, no indications of either coactivation or crosstalk could be detected, and

crosstalk (without coactivation) could be detected in only two contractions.

Signals detected on the back muscles were almost an order of magnitude smaller than those detected on the tibialis anterior (TA). The initial CV of both back muscles was higher than in the TA, suggesting either different fiber type and/or size distribution, or bias errors due to electrode-fibers misalignments. Initial MDF was slightly higher in the TA, probably because of the thinner layer of fat and fascia interposed between the TA and the skin. As observed in the TA, the recruitment order of motor units of the back muscles was not consistent, showing either increase or decrease of initial CV as stimulation amplitude was increased. During fatiguing contractions, CV decreased faster in the TA than in either the LD or ILC and decreased faster in the LD than in the ILC.

Future Plans/Implications—The technique needs improvement in order to obtain more consistent and

acceptable signals from different subjects; repeatability studies must be performed to assess intra-subject variability. However, this method shows promise for the selective activation and characterization of individual back muscles.

Recent Publications Resulting from This Research

Characterization of Back Muscles by Means of Electrical Stimulation. DeLuca CJ et al., in Proceedings of the 11th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 1041-1042, Seattle, 1989.

[289] Control Properties of Lower Back Muscles

C.J. DeLuca; K.R. Murthy; T. Sciascia; G. Kamen

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Sponsor: VA Rehabilitation Research and Development Service (Project #B596-RA, Part 1)

Purpose—Our recent investigations have used surface electrodes to study the performance of lower back muscles in an effort to address the issues surrounding low back pain. In as much as these muscles are not well understood, we have also become interested in characterizing the properties of these muscles. Thus, this study focuses on the manner in which motor units are controlled during contractions of muscles of the lower back.

Since it was not clear that our indwelling needle electrode recording technique could be implemented in the lower back, a pilot experiment was performed to assess the feasibility of such an approach. We were able

to successfully extract the motor unit firing behavior of the longissimus muscle in this experiment. Having demonstrated the ability to acquire motor unit myoelectric signals from back muscles, we plan to begin a detailed study of the firing behavior of low back muscles in an effort to characterize the control properties of these muscles. We hope that these data will allow us to determine whether the muscles of the lower back are controlled in a manner different from the control of other previously studied skeletal muscles. Moreover, these studies will also assist our ongoing investigations involving biomechanical modeling of the lower back by reducing the inherent redundancies in the model.

[289a] Fundamental Analysis of Postural Sway

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Sponsor: VA Rehabilitation Research and Development Service (Project #B596-RA, Part 2); Whitaker Foundation; Liberty Mutual Insurance Company

Purpose—The task of maintaining an upright posture involves the integration of sensory information from three different systems: the visual system, the vestibular system, and the proprioceptive system. The multiple number of muscles involved and the inherent instability in the task cause the center of gravity of the body and the center of pressure underneath the feet to move even while the individual is trying to maintain a fixed posture. A stochastic analysis of the motion of the center of pressure as recorded by a force-plate revealed the existence of two components: a random component and a periodic circular component.

The random component is characteristic of the motion of particles performing random movement (e.g.,

a diffusing molecule). The periodic component is characteristic of the motion of a particle performing a circular motion at a constant angular velocity. A theoretical model that combines the two components is suggested as a conceptual description of the two elements identified in actual measurements of the motion of the center of pressure. A new parameter that quantifies the relationship between the periodic and the random components was developed. This parameter is being examined as an objective measure of the degree of randomness that characterizes the postural control capacity of an individual subject.

[290] Experimental Investigations of Common Drive Behavior in Human Motor Units

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Sponsor: *Liberty Mutual Insurance Company*

Purpose—We have described in previous reports a novel phenomenon of motor unit firing behavior in which concurrently active motor units modulate their firing rates in a unified fashion. Our goal in this experiment was to further our understanding of this common drive behavior.

Progress/Results—The muscle spindle has been implicated as one possible source of this common firing rate fluctuation. We endeavored to measure motor unit firing rates in a facial muscle devoid of muscle spindles, the

orbicularis oris. Approximately 21 motor units were analyzed from a total of 5 subjects. The results indicate that common drive behavior can indeed be observed in the absence of muscle spindles. While muscle spindles may contribute to this firing rate fluctuation in other muscles, it is clear that this effect in muscles devoid of muscle spindles is mediated by skin receptors, or other stretch-type receptors, or some central nervous mechanism.

This work was presented at the annual meeting of the Society for Neuroscience, Phoenix, AZ, 1989.

[291] Muscle Fatigue Correlates for Concurrent Myoelectric and NMR Measurements

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Sponsor: *Liberty Mutual Insurance Company*

Purpose—The physiological correlates to the observable shift in the electromyography (EMG) signal frequency spectrum during fatigue are not completely understood. Although it is widely accepted that this spectral shift is related to a slowing of EMG signal conduction velocity, the extent to which this phenomenon is related to a change in pH or energy sources within the muscle is not clear. The precise relationship between cellular biochemical events and the electrical manifestation of muscular fatigue has eluded investigators. One of the principal obstacles has been the invasive nature of available techniques to measure intramuscular substrates and metabolites. However, with recent technical advances in phosphorous nuclear magnetic resonance spectroscopy (31P-NMR), intramuscular pH, and other cellular biochemical events can be noninvasively assessed in resting or exercising muscle.

Progress—We have completed the modification and testing of myoelectric and torque measuring devices to ensure compatibility with the high magnetic fields

characteristic of NMR instrumentation. This work was pursued through the collaborative efforts of the NeuroMuscular Research Center and the Nuclear Magnetic Resonance Laboratory at the Brigham and Women's Hospital.

Results/Implications—Preliminary measurements have been completed for 2 subjects (a total of 10 tests) to identify optimal contractile force levels and test durations for establishing a protocol that will accommodate the signal requirements of both methodologies. This procedure has enabled us to monitor the change in median frequency as a function of time during and following a sustained fatiguing contraction. The median frequency behavior has been compared to concurrent measures of pH and muscular high-energy phosphate following pilot studies on the tibialis anterior, gastrocnemius, and upper trapezius muscles.

Future Plans—Future goals include developing protocols to establish causality between physiological measures and spectral parameters of the myoelectric signal.

[292] Myoelectric Changes During Fatigue

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Sponsor: Liberty Mutual Insurance Company

Purpose—Many studies have shown that during a sustained muscle contraction there is a shift in the myoelectric signal spectrum toward lower frequencies. This shift has been attributed to a decrease in the velocity of propagation of individual muscle fiber action potentials. However, conduction velocity changes measured on the surface of the muscle cannot completely account for the observed spectral shifts. This study analyzed the myoelectric signal during fatigue with both indwelling needle and surface electrodes in order to compare results obtained both on the surface and inside the muscle.

Preliminary Results/Future Plans—As observed in previous experiments, this study showed that the rate of

decline in median frequency was greater than that seen in conduction velocity. The selective needle signals were decomposed using myoelectric signal processing and decomposition algorithms, in order to analyze the effects of fatigue on individual motor units. Preliminary analysis shows that there was no increase in synchronous firing behavior, and there was no evidence of change in the number of active motor units near the recording electrode during fatigue.

The selective needle signals are currently being analyzed for relative changes in individual motor unit conduction velocity, which will be compared to changes in spectral parameters of these myoelectric signals to see if the relationship detected at the surface is also observed within the muscle.

[293] Muscle Fatigue Monitor (MFM) Update

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Sponsor: Liberty Mutual Insurance Company

Purpose—The concept of plotting changes in the spectra of the myoelectric signal as an indicator of fatigue had its origins over 20 years ago. However, practical signal processing techniques to measure this phenomenon have only recently emerged as a result of advances in electronics and computer technologies. The Muscle Fatigue Monitor (MFM) conceived by our Center has similarly evolved from a crude prototype into a sophisticated computer-based system capable of processing 10 channels of myoelectric data in real time. The present system allows researchers to investigate the fatigue process of more complex muscular activities, such as those involving the muscles of the lower back or of the hand and wrist. During the past 2 years, this system has been used extensively in our Muscle Fatigue Laboratory to generate a detailed picture of back performance and its relationship to episodic back pain. This research application has

proven to be a key element in obtaining consistent, objective, and reliable measurement of muscular activity from the lower back.

Progress—In an effort to expand applications into new environments, we have installed additional MFM systems in both clinical and university settings. Units have been placed at Boston City Hospital, Rush-Presbyterian-St. Luke's Medical Center, Queen's University in Canada, and Michigan State University. A fifth MFM system, installed at the Liberty Mutual Research Center, will be used to investigate fatigue of the hand and wrist in a simulated industrial environment.

Future Plans—The upcoming year will focus on the continued integration of the MFM technology in clinical applications.

[294] Electromyographic Spectrum Analysis of Paraspinal Muscles: Changes Following Physical Training

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Sponsor: *Medical Research Council of Canada; Physicians' Services, Inc. Foundation; Ontario Ministry of Health*

Purpose—It has been suggested that electromyographic power spectrum analysis (EMG-PS) of the paraspinal muscles has two major clinical purposes in the area of low back pain: 1) patient status evaluation; and, 2) treatment outcome evaluation. While the usefulness of EMG-PS in differentiating back pain patients from controls has been demonstrated, no information is available on the sensitivity of this methodology to muscle adaptations resulting from physical therapy (e.g., increased oxygenation, metabolic capacity, cross-sectional muscle fiber area). We are investigating the relationship between changes in fitness parameters (related to such adaptations) and changes in EMG-PS parameters in two studies.

Progress—*Study 1.* Previously sedentary healthy women are undergoing fitness tests (which determine aerobic capacity, strength, flexibility, body composition), and EMG-PS of the iliocostalis and multifidus muscles, before and after a 12-week period, during which they volunteer to attend 3 to 5 fitness classes per week. These data are being compared to those of control subjects who remain sedentary.

Study 2. A similar investigation is being carried out with low back pain sufferers who participate in the University Back School program (10-week duration).

[295] Electrode Array Signal Processing

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Sponsor: *Medical Research Council of Canada*

Purpose—The main purpose of this study is to improve evoked response measurement signal-to-noise ratio (SNR) by the use of array beamforming.

Progress/Results—A delay and sum array beamformer has been analyzed and implemented. The results demonstrate that the array can, depending on the cross-channel correlation, improve SNR by a factor equal to the number of electrodes in the array.

Recent Publications Resulting from This Research

A Multi-Electrode Array for the Acquisition of Somatosensory Evoked Potentials. McKinley CA, Masters thesis, Department of Electrical Engineering, University of New Brunswick, 1989.

A Multi-Electrode Array in Ensemble Averaging of Evoked Potentials. McKinley C, Parker PA, in Proceedings of the Canadian Medical and Biological Engineering Conference, Toronto, 75, 1989.

A Beamformer for the Acquisition of Evoked Potentials. McKinley CA, Parker PA, IEEE Trans Biomed Eng (accepted for publication).

[296] Postural Muscle Adaptability During Prolonged Spaceflight

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Sponsor: *National Aeronautics and Space Administration (NASA); NeuroMuscular Research Center*

Purpose—The Center's experience in implementing techniques to measure muscle fatigue noninvasively and objectively will be applied to a comprehensive investigation of the effects of prolonged spaceflight (microgravity)

on the vestibular and motor systems of the body. This project is a component of the NASA shuttle program involving the Spacelab Life Science (SLS-01) mission. This mission represents the first shuttle flight dedicated

entirely to the medical and biological effects of spaceflight. Our contribution to the project will be directed at electromyographic (EMG) measurements of postural muscle adaptation to microgravity.

Progress—A protocol using surface EMG was formulated and tested to evaluate changes in EMG spectral measures of fatigue and conduction velocity for several postural muscles of the lower limb.

Future Plans/Implications—Measurements will be conducted preflight and immediately postflight on

members of the shuttle crew. The Muscle Fatigue Monitor and associated signal-processing software will be used to measure EMG spectral parameters and conduction velocity. When completed, we hope to demonstrate the use of the technique for documenting the adaptability of postural muscles to microgravity. This information will complement related studies on vestibular function and spaceflight conducted by Massachusetts Institute of Technology. Successful development of prophylactic exercises for future spaceflight will most likely be dependent on objective measures of this kind.

[297] Mechanism of Torque Generation in the Frog Hindlimb

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Sponsor: *National Institute of Arthritis and Musculoskeletal and Skin Diseases, National Institutes of Health*

Purpose—The objective of this project was to understand the relationship between muscle and joint properties during torque generation. Muscle sarcomere length and moment arm were measured in the frog hindlimb (*Rana pipiens*) at 10-degree knee and hip joint angle increments. Knee and hip torque were also directly measured over the same range.

Results/Implications—The major finding of this study was that the joint angle at which muscle force was maximum, was neither the joint angle at which moment arm

was maximum, nor the angle at which joint torque was maximum. These data suggest that muscle fiber length relative to moment arm magnitude have a major impact on the nature of torque generation at a particular joint.

Recent Publications Resulting from This Research

Hypothesis: Biarticular Muscles Transfer Moments Between Joints.
Lieber RL, Dev Med Child Neurol 32:456-458, 1990.
Interaction Between Semitendinosus Muscle and Knee and Hip Joints During Torque Production in the Frog Hindlimb. Mai MT, Lieber RL, J Biomech 23:271-279, 1990.

[298] Physiological Significance of Tendon Compliance

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Sponsor: *National Institute of Arthritis and Musculoskeletal and Skin Diseases, National Institutes of Health*

Purpose/Methodology—The purpose of this study was to understand the relationship between tendon and muscle mechanical properties. We measured tendon properties during passive loading and during isometric muscle contraction. The pelvis-tendon-ST muscle-tendon-tibia complex (BTMTB complex) was isolated from 10 grass frogs (*Rana pipiens*). Dye lines were applied to mark regions of the tendon, aponeurosis, and muscle. Pelvic and tibial bones were clamped into a testing jig immersed in physiological saline (21 degrees C). The muscle was

maximally activated to measure maximum contractile tension (P_o). The BTMTB complex was then loaded at a constant rate of about 3% $P_{o/s}$ while measuring force and videotaping the applied dye lines. Using load-time and strain-time values (as measured off-line using a video dimensional analyzer), tendon load-strain, and stress-strain relations were generated.

Results/Implications—Tendon strain corresponding to P_o was approximately 3%. Tendon stress at P_o was

approximately 2 MPa. In addition, at physiological contraction velocities, the tendon was relatively stiffer, suggesting that the viscoelastic properties were significant, even at low velocities. The results also demonstrate that tendon compliance is sizeable even in the physiological range, and cannot be assumed to be negligible.

Recent Publications Resulting from This Research

Measurement of Frog Semitendinosus Force, Tendon Load-Deformation and Load-Strain Properties. Lieber RL, Leonard ME, J Biomech 22:1048, 1989.
Frog Semitendinosus Tendon Mechanical Properties During Passive Loading and Active Muscle Contraction. Lieber RL, Trestik CL, Leonard ME, J Biomech (in press).

[299] Skeletal Muscle Architectural Design

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Sponsor: National Institute of Arthritis and Musculoskeletal and Skin Diseases, National Institutes of Health

Purpose/Methodology—The purpose of this project was to elucidate the design of various mammalian skeletal muscles. In the rabbit hindlimb, the detailed fiber arrangement of 26 muscles was measured and submitted for discriminant analysis for determination of the structural factors which most strongly differ between functional groups.

Results/Implications—In general, hamstrings and dorsiflexors were composed of relatively long fibers with relatively low physiological cross-sectional areas. Conversely, the antigravity quadriceps and plantarflexors were generally more highly pennated, with relatively short fibers and large cross-sectional areas. Similar degrees of specialization were observed in the human

forearm. These data indicate that skeletal muscles are “smart” in that they perform the needed task (force or excursion/velocity) by virtue of their intrinsic design, and not by virtue of extremely sophisticated sets of neural command signals.

Recent Publications Resulting from This Research

Architecture of Selected Human Forearm Muscles: Functional Implications for Tendon Transfer. Lieber RL, Fazeli BM, Botte MJ, in Transactions of the 35th Orthotics Research Society, 14:198, 1989.
Skeletal Muscle Architecture of the Rabbit Hindlimb: Functional Implications of Muscle Design. Lieber RL, Blevins FT, J Morphol 199:93-101, 1989.
Architecture of Selected Wrist Flexor and Extensor Muscles. Lieber RL, Fazeli BM, Botte MJ, J Hand Surg 15:244-250, 1990.

[300] Selective Muscle Fiber Damage Due to Eccentric Contraction

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Sponsor: National Institute of Arthritis and Musculoskeletal and Skin Diseases, National Institutes of Health

Purpose/Methodology—The purpose of this project was to determine the mechanism of damage in muscle fibers from the rabbit tibialis anterior. Muscles were cyclically stretched 25% of their fiber length every 2 seconds for 30 minutes.

Results/Implications—Force declined significantly after eccentric contraction (EC) compared to either isometric contraction or passive stretch. In addition, fibers from EC muscles demonstrated focal regions of ultrastructural abnormalities and light microscopic damage to the fast-glycolytic (FG) fibers. These data suggest that the FG

fibers might be particularly vulnerable to EC-induced damage and may also explain why previous training attenuates the magnitude of EC-induced damage.

Recent Publications Resulting from This Research

The Effect of Varied Strain on Muscle Damage During Eccentric Exercise of the Rabbit Tibialis Anterior. Lieber RL et al., in Transactions of the 35th Orthotics Research Society, 14:295, 1989.
Immunohistochemical Identification of Cytoskeletal Damage in Muscle Cells Subjected to Eccentric Exercise. Lieber RL, Friden JO, in Transactions of the 36th Orthotics Research Society, 36:542, 1990.

[301] Utility and Physiology of Botulinum Toxin for Involuntary Movement Disorders

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Sponsor: *National Institute of Neurological Disorders and Stroke, National Institutes of Health*

Purpose/Methodology—Botulinum toxin injected in small doses directly into muscle binds to the neuromuscular junction and inactivates it for approximately 3 months. This treatment has been demonstrated to be useful for strabismus and blepharospasm, but the mechanism of action is not completely understood. Studies of utility of botulinum toxin have been carried out in spasmodic dysphonia and writer's cramp and its variants (such as pianist's cramp). Treatment appeared effective in both, and we are enlarging our experience with writer's cramp to see if we can determine which patients are more

likely to improve. A double-blind trial was started for writer's cramp.

Progress/Results—Studies of the physiology of the mode of action have been carried out in spasmodic dysphonia, writer's cramp, blepharospasm, and hemifacial spasm. These studies show that the major effect of botulinum toxin is to weaken the muscle that is in spasm. Electromyogram studies in writer's cramp, blepharospasm, and hemifacial spasm show that spasms continue, but muscles are ineffective. No other changes in physiology were identified.

[302] Biological Signal Processing

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Sponsor: *Natural Sciences and Engineering Research Council of Canada*

Purpose—Our purpose was to determine the effects of various physiological parameters of skeletal muscle on myoelectric signal and the control performance of myoelectric control systems.

Progress—To date, an extensive study has been carried out to investigate the effects of firing rate statistics, endplate dispersion, action potential shape, and number of units on the control performance of a myoelectric control system. The performance equations have been derived and the results verified by simulation and *in vivo* experimental work.

Recent Publications Resulting from This Research

Analysis of the Myoelectric Communication Channel. Zhang YT, PhD diss., University of New Brunswick, 1990.

A Study of the Effects of Motor Unit Recruitment and Firing Statistics on the Signal to Noise Ratio of a Myoelectric Control Channel. Zhang YT, Parker PA, Scott RN, Med Biol Eng Comput 28(3):225-231, 1990.

Control Performance Characteristics of Myoelectric Signal with Additive Interference. Zhang YT, Parker PA, Scott RN, Med Biol Eng Comput (accepted for publication).

[303] Coordination of Muscles in Gait

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Sponsor: *Netherlands Organization for Research, Foundation of Biophysics*

Purpose—The coordination of lower limb muscles has been studied when one is jumping up and down and when bicycling. Rules for the function of biarticular

muscles were found. This project is to ascertain if these rules are applicable during normal walking and running.

Progress/Results—Biarticular muscles play a unique role in transporting rotational energy from proximal to distal segments when a person jumps up and down. The muscles contribute to the mechanical goal of the movement—maximizing effective power at take-off. They compensate for the diminishing contribution to translation of the body's center of gravity by extension (rotation) of lower limb segments.

Timing of the activation of these muscles, as well as the fact that they co-contract with their antagonists, is important. In bicycling, it appeared essential that such co-contractions were instrumental in producing thrust, as well as direction of movement in the extending limb.

We have tried to validate these concepts in human walking and running by experimenting and modeling. In gait, biarticular hamstring and rectus femoris muscles are active in early stance. They co-contract with monarticular hip and knee extensors, and tune hip and knee movements while the leg is shortening and lengthening (knee flexion), regulating the level of potential energy.

This result will be compared with those of the running and jumping studies.

Future Plans—Jumping up and down, and the timing and geometrical properties of the system will be analyzed by modeling. A model (SPACAR) has been developed that applies finite element analytic instruments to problems of dynamics. Force platform, movement, and the electromyographic registration of long jumps, running, and walking will be analyzed using this model.

Recent Publications Resulting from This Research

The Unique Action of Bi-Articular Muscles in Leg Extensions.

Van Ingen Schenau GJ, Bobbert MF, Van Soest AJ, in *Multiple Muscle Systems: Biomechanics and Movement Organizations*, 639-652, J. Winters, S.L.-Y. Woo (Eds.). New York: Springer-Verlag, 1990.

The Activation of Mono- and Bi-Articular Muscles in Multi-Joint Movements. Gielen S et al., in *Multiple Muscle Systems: Biomechanics and Movement Organizations*, 302-311, J. Winters, S.L.-Y. Woo (Eds.). New York: Springer-Verlag, 1990.

[304] Skeletal Muscle Reaction to Immobilization

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Sponsor: Netherlands Organization for Research, Foundation for Biological Sciences

Purpose—The purpose of this study was to predict the reaction of human skeletal muscle to immobilization regarding length, duration of immobilization period, and position of the limbs.

Progress—A muscle model, relating the architecture of the skeletal muscle to its functional capacity, was formulated and experimentally determined on rat calf muscle and various others. Application to human calf muscle, using morphological data of human cadavers was done. The model was also applied in a description of muscular growth. It is now being used in analyzing the effects of various periods of immobilization in different positions, leading to differing muscle lengths.

The work is part of a program on "form, function and coordination of skeletal muscles," in which we have tried to relate experimental analysis of animal muscular function to real life human movements in vertical jumping and running.

Results—Effects of 4- to 6-weeks immobilization of calf muscles in growing rats were studied. Slow twitch soleus muscle followed the general rule: sarcomeres were lost during immobilization in shortened position. Predominantly fast and pennated gastrocnemius muscle reacted with alterations in muscle fiber length and sarcomere number, as well as alterations in aponeurotic length. Depending on the period of immobilization, these reactions resulted in abnormal length-force relations normalized to optimum length and maximal force at that length after 4 weeks. After 6 weeks these relations were normal, suggesting that the tissues of the muscle were harmoniously working together again. In short-term immobilized muscles, the reactions of muscular and connective tissue components in pennated muscle were not functionally balanced.

Future Plans—The interrelationships of muscular and connective tissue in growing and functioning muscle will be studied in more detail.

Recent Publications Resulting from This Research

Properties of the Tendinous and Series Elastic Component of EDL Muscle-Tendon Complex of the Rat. Ettema GJC, Huijing PA, J Biomech 22:1209-1215, 1989.

Architecture and Elastic Properties of the Series Elastic Element of Muscle-Tendon Complex. Ettema GJC, Huijing PA, in

Multiple Muscle Systems: Biomechanics and Movement Organizations, 57-68, J.M. Winters, S.L.-Y. Woo (Eds.). New York: Springer-Verlag, 1990.

Series Elastic Properties and Architecture of Skeletal Muscle in Isometric and Dynamic Contractions. Ettema GJC, PhD diss., Vrije Universiteit, Amsterdam, 1990.

[305] EMGGEN: A Software Package for Myoelectric Signal Generation

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Sponsor: *NeuroMuscular Research Center; Politecnico di Torino; Liberty Mutual Insurance Company*

Purpose—We have implemented a computer model to investigate the relationships between the myoelectric signal generation mechanisms and their spectral and amplitude parameters. The modular software package may be used to study different techniques for estimating the average muscle fiber conduction velocity, and to synthesize test signals to allow objective evaluation of the accuracy of myoelectric signal decomposition algorithms.

Methodology—The package, EMGGEN, is based on an extended version of the Lindstrom's model. It allows the user to synthesize either surface or internal myoelectric signals, simulating voluntary or electrically elicited contractions. Both monopolar and bipolar electrodes may be simulated, as well as single differential and double differential signals.

EMGGEN consists of two sections. The first allows the user to build the myoelectric signal interactively by choosing the number of active motor units, as well as

the depth and distance between the electrode location and the innervation zone, the initial conduction velocity and its variations during the contraction, the firing rate, and the inter-pulse interval variability for each unit. During the interactive section, the user can verify the effect of each choice in both frequency and time domain by means of graphics and numerical values. At the end of the interactive section, a report file automatically summarizes the characteristics of the signal to be generated. The second section generates the signal starting from the data that was interactively entered by the user. The user interface has been designed to be as friendly as possible. A detailed manual describing EMGGEN is available. Program EMGGEN runs under the VAX/VMS operating system.

Future Plans/Implications—A more powerful version of the program, specifically oriented to computer-aided instruction, will soon be available for IBM-AT or 386-based machines.

[306] Portable 8-Channel Myoelectric Preamplifier

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Sponsor: *NeuroMuscular Research Center*

Purpose—An increased number of investigations conducted at the NeuroMuscular Research Center (NMRC) have created the need for a preamplifier that is both portable and capable of processing simultaneous multiple myoelectric signals. The NMRC Design Laboratory has developed an 8-channel preamplifier to address this need. The system consists of an 8-channel belt-mounted preamplifier module, 50-foot umbilical cable, and power supply

box. It is used in conjunction with our improved "standard" electrodes, making it fully compatible with the muscle fatigue monitor (MFM) systems and equipment.

Methodology/Progress—The preamplifier is produced on a custom-printed circuit board and designed to provide subject safety by incorporating total galvanic isolation between the standard surface electrodes and signal

processing instrumentation. Other design features include variable gain and channel select function, and bandpass filters to remove frequency components of signals that are outside the range of interest.

Application for the preamplifier system include gait analysis, remote workstation testing, and automobile studies. Three units have been built and are currently in use in several investigations.

[307] EMG Evaluation of Car Seats Associated with Fatigue and Muscle Activity

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Sponsor: Nissan Research & Development, Inc.

Purpose—A collaborative study between the NMRC and the Massachusetts Institute of Technology (MIT) was recently supported by the Nissan Motor Company to develop new criteria for evaluating automobile seating. A pilot study was conducted to demonstrate the feasibility of using a surface electromyographic (EMG) array of electrodes to monitor muscle fatigue during prolonged periods of highway driving. Pilot studies by the Department of Mechanical Engineering at MIT were also conducted. MIT developed and tested a multi-dimensional scaling technique to analyze psychometric components of fatigue associated with driving. The EMG and multidimensional scaling techniques are combined in the present study with concurrent measurements of body motion using a three-dimensional position sensor.

Methodology—The measurement system is presently being used to analyze five different car seats provided by the engineering staff of Nissan Motor Company. Five

subjects will be tested for each of the seats, which include a standard production seat and four prototype seats, each with very different design features. The seats are being tested under actual driving conditions over a 4-hour test period. Nine muscle sites from the neck, shoulders, upper and lower back, and right lower limb are monitored by the EMG array. Repeat tests have been incorporated into the protocol to assess the reproducibility of results on different days and in different subjects.

Following completion of data collection, EMG spectral parameters and amplitude parameters will be averaged across subjects and compared for each seat. Physiologic and psychometric fatigue indices will be correlated to body movement and muscle activity to identify which car seat designs limit fatigue during driving.

Implications—If successful, procedures developed for this study may be applied to assess other design factors of the automobile interior that reduce fatigue and thereby improve the safety and comfort of the driver.

[308] EMG Power Spectrum and Histological Analysis: Percutaneous Biopsies

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Sponsor: Ontario Ministry of Health, Physicians' Services, Inc. Foundation

Purpose—In order to investigate the hypothesis, based on electromyogram (EMG) power spectrum investigations, that some patients displayed an EMG profile which is indicative of a deficient endurance capacity in the multifidus muscle, a study was initiated to collect muscle specimens for histological analysis. The study involved the use of the Stille-Eriksson biopsy needle which has

been recommended for tissue sampling of the erector spinae muscles.

Progress—Explorative investigations with the Stille-Eriksson needle on patients who were seen for surgery led us to question the clinical usefulness of the needle. Changes on the needle failed to improve its performance

sufficiently for reliable histochemical analysis. Based on these observations, it was decided that a direct incisional biopsy technique offers a safer and less traumatic way of obtaining suitable muscle specimens from superficial paraspinal muscles.

Implications—Studies are required to examine the validity of proposed relationships between EMG parameters

of the power spectrum and the actual histochemical composition of the muscle. This investigation should be useful in identifying clinically appropriate muscle specimen collection procedures.

Recent Publications Resulting from This Research

Percutaneous Biopsies with the Stille-Eriksson Needle. Biedermann HJ, Shoemaker PJ, *Internat J Sports Med* 11(2):168, 1990.

[309] Temporomandibular Joint Pain Syndrome: EMG Power Spectrum Analysis of the Masseter and Temporalis Muscles Before and After Occlusal Splint Therapy

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Sponsor: Ontario Ministry of Health, Physicians' Services Inc. Foundation

Purpose—Current dental treatment interventions for chronic temporomandibular joint syndrome (TMJS) are predominantly based on neuromuscular theories that implicate hyperactivity of the masticatory muscles due to dental malocclusion, leading to muscle fatigue and, consequently, pain. The treatment rationale is to reduce tension levels in the masticatory muscles by correcting dental malocclusion, usually by occlusal splinting. A major problem with this theoretical approach is that the expected post-treatment reductions in masticatory muscle EMG levels have not always been found, and where they have occurred, they have not been correlated with subjective and clinical signs of improvement.

We suggest that TMJS treatment studies employing EMG amplitude measures may have failed to find changes consistent with clinical outcomes because such measures provide inadequate information, permitting only a limited insight into the functional characteristics of the masticatory muscles (i.e., degree of tension/relaxation). Rather than resulting from a simple reduction in muscle tension level, clinical improvement in TMJ pain patients treated by the above methods may, in fact, be due to a reduction in *fatiguability* due to muscle adaptation to changes in functional demand.

If this hypothesis is correct, EMG power spectrum analysis, not rectified mean squares (RMS) comparison, is the appropriate outcome measure in the study of TMJS. Power spectrum analysis offers information regarding both muscle function and corresponding morphological characteristics (i.e., muscle fatigue and

recovery, fiber-typing, fiber type recruitment patterns) that would not be reflected in measures limited to amplitude of the EMG signal.

A number of investigators have examined power spectrum characteristics of the masticatory muscles under conditions of fatigue in symptom-free normal subjects. These studies have consistently shown a shift in the EMG power spectrum of the masseter and anterior temporalis muscles to lower mean frequencies during maximal or submaximal voluntary clenching indicating metabolic fatigue in the muscle. To date, however, power spectrum investigations of masticatory muscle fatigue have been limited to normal subjects.

Progress—We have recently initiated a study that will evaluate both EMG power spectrum and RMS parameters in TMJ pain patients undergoing occlusal splint therapy. Because power spectrum recording technique relies on surface electrodes, and because the frequency parameter changes are related to changes in the conduction velocity of the muscle fibers, the proper placement of surface electrodes with respect to muscle fiber direction is essential in order to obtain parameters that can be interpreted with respect to the histochemical structure of the muscle under investigation. So far, placement of the electrodes in power spectrum investigations of the masseter and temporalis muscles has been determined by muscle palpation and reference to external anatomical landmarks. The validity of these external criteria, however, in identifying accurately the anatomical direction of the underlying muscle fibers,

has yet to be demonstrated. A preliminary cadaveric study was therefore necessary to address this concern.

Results—A cadaveric study revealed a number of surface landmarks, easily palpable through the skin, that can be used reliably to identify the direction of masseter and

temporalis muscle fibers, and to guide the placement of surface electrodes.

Implications—Given these findings, reliable EMG power spectrum investigations of the masseter and temporalis muscles can now be undertaken.

B. Ligaments and Tendons

[310] Laser Biostimulation of Healing Tendons: Effects of Treatment Parameters

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Sponsor: VA Rehabilitation Research and Development Service (Project #A534-RA)

Purpose—Experimental observation of developing collagen fibrils in membrane-bound intracytoplasmic vesicles is a baffling phenomenon which contradicts the biochemical dogma that polymerization of pro-collagen molecules into collagen fibrils occur extracellularly with native periodicity. However, because this phenomenon is commonly observed in collagen-producing cells exposed to antitubulin agents, anabolic steroids, and disease processes, it is acknowledged as an evidence of rapid collagen turnover. Since laser photostimulation has been shown to modulate collagen synthesis, the ultrastructure of regenerating tendons exposed to a low intensity Ga-As laser beam was studied: 1) to determine if laser treatment induces the presence of vacuolar fibrils; and, 2) to describe the ultrastructure of laser photostimulated tendon fibroblasts.

Methodology/Progress—The right calcaneal tendons of nine rabbits were surgically tenotomized, repaired, and immobilized in plaster. Beginning from the first day after surgery, the tenotomized tendons of six rabbits were exposed to a Ga-As laser beam of 904 nm wavelength and 7 mW average power. The beam was applied transcutaneously every day, pulsed 2,336 times per second, and both treatment duration and irradiation area varied to yield an energy density of either 4 J cm^{-2} (three rabbits) or 5 J cm^{-2} (three rabbits). The tenotomized tendons of the

remaining three rabbits were not exposed to a laser beam; thus, these tendons served as tenotomized nontreated controls. The right calcaneal tendons of three other rabbits served as normal intact nontenotomized controls. On the fourteenth postoperative day, neotendons were surgically excised from the site of tenotomy of each tendon, processed for electron microscopy, then visualized and photographed under a Philips 300 or a JOEL 100CX electron microscope. Vacuolar fibrils were observed exclusively in the fibroblasts of laser photostimulated tendons. The vacuolar fibrils had the same spatial orientation as those matrical fibrils within their immediate vicinity. Thus, in transverse, oblique, and longitudinal sections, matrical and vacuolar fibrils were correspondingly transverse, oblique, or longitudinal in appearance. Longitudinal sections revealed that vacuolar fibrils had the characteristic banding pattern of collagen, as did matrical fibrils. No other ultrastructural differences were observed between laser-treated tendons and tenotomized nontreated controls. In line with previous reports, sections of the regenerating tendon were remarkably different from those of intact nontenotomized tendons.

Implications—These findings suggest that exposure to laser beam promotes rapid collagen turnover in regenerating rabbit calcaneal tendons.

[311] Treatment of Variable Partial Flexor Tendon Lacerations

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Sponsor: VA Rehabilitation Research and Development Service (Project #A505-RA)

Purpose—Penetrating trauma to the hand often produces partial lacerations of the digital flexor tendons. While primary surgical repair of complete flexor tendon lacerations has been generally accepted, the role for tenorrhaphy in the management of incomplete tendon injuries has remained controversial. The goal of this project was to develop a controlled animal model of partial flexor tendon injuries. The model was then to be used in studying the effects of different repair techniques on the healing of partial tendon lacerations.

Methodology—In preliminary investigations, we developed an instrument we called the “tenotome” which allowed us to produce very consistent partial tendon lacerations. The tenotome was used to produce accurate 75% lacerations of the flexor profundus tendons of 220 adult female chickens. The animals were randomized to groups studying: 1) unrepaired tendons; 2) epitendinous repairs with 7-0 Prolene; or, 3) modified Kessler repairs with a 5-0 core suture and a 7-0 epitendinous stitch. In a fourth group, the tendons were exposed, but not lacerated, to serve as a control. All of the chickens were placed postoperatively in rubber-band splints, allowing immediate constrained digital motion while protecting the tendon repairs. At intervals of 0 to 60 days, the animals were killed with an overdose of IV KCl, and the tendons were harvested for biomechanical testing of tendon repair strength and tendon gliding.

Results—The rupture strengths immediately postrepair (day 0) averaged 53.96 N for the unrepaired group; 54.15 N for the epitendinous repairs; and 56.80 N for the modified Kessler group. The unrepaired tendons and the epitendinous repairs showed modest insignificant losses in repair strength at 10 and 20 days, with gains in strength at the 40- and 60-day intervals. There were no significant differences in strength between the unrepaired tendons and epitendinous repairs at any time interval. In contrast, the lacerations repaired with a modified Kessler suture

showed significant losses in repair strength at the 10- and 20-day intervals, with failure to return to baseline strength by 60 days. The tendons repaired with a modified Kessler suture were significantly weaker than the other groups at all intervals after day 0 ($p < 0.05$). There were 6 *in vivo* tendon ruptures among the 30 tendons repaired with a modified Kessler stitch, while the unrepaired tendons and the epitendinous group had only a single tendon rupture each.

The modified Kessler repairs also showed increased edema and adhesions around the repair site when compared to unrepaired tendons or those with epitendinous repairs. The subjective observation of increased adhesions was confirmed with objective tests of tendon gliding. Partial lacerations which had not been sutured, or sutured with epitendinous stitches only, showed nearly normal flexion of the DIP joints distal to the repair site. In contrast, the modified Kessler repairs showed severely restricted DIP joint flexion due to dense adhesions around the repair site.

Implications—Partial tendon lacerations can be repaired with epitendinous sutures without producing the adverse effects seen with placement of large core sutures in the modified Kessler technique. Judicious clinical use of epitendinous sutures to repair loose tendon flaps should help minimize the mechanical complications of tendon triggering, entrapment of tendon flaps, late rupture, and adhesion formation.

The animal model and techniques developed in this study should prove very useful in future studies of flexor tendon healing.

Recent Publications Resulting from This Research

The Effect of Different Repair Techniques on the Strength of Partial Flexor Tendon Lacerations Over Time. Hitchcock TF et al., Abstracts of the 35th Annual Meeting of the Orthopaedic Research Society, 14:275, 1989.

New Technique for Producing Uniform Partial Lacerations of Tendons. Hitchcock TF et al., J Orthop Res 7(3):451-455, 1989.

[312] Structural and Functional Properties of Normal and Healing Ligaments: Part 1

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Sponsor: VA Rehabilitation Research and Development Service (Project #A188-3RA)

Purpose—We have developed a new injury model to study medial collateral ligament (MCL) healing in the rabbit. Although many experimental animal models have been used to examine MCL healing, few have included a concomitant injury to the ligament in sections to bone as observed clinically. Using a combined injury model, long-term healing was evaluated following conservative treatment or primary repair of the MCL.

Methodology—In both groups (repaired and nonrepaired), the left MCL of each animal was surgically exposed, and a 2.5 mm diameter stainless steel rod was passed transversely beneath the ligament at the joint line. A small notch was made on each side of the MCL at the level of the rod. The ligament was ruptured in tension by pulling on the rod, creating a “mop-end” midsubstance tear. In half of the animals, the torn ligament ends were surgically repaired, while those of the remaining animals were manually approximated. At 6, 12, and 52 weeks postoperatively, one-third of the animals in each group (repaired and nonrepaired) were sacrificed, and healing of the MCL was evaluated by comparing the varus-valgus (V-V) knee rotation, the structural properties of the femur-MCL-tibia complex (FMTC) and the mechanical properties of the MCL substance.

Results—No significant differences were seen in the V-V rotations or the tensile properties between the repaired and nonrepaired groups at either 6, 12, or 52 weeks, suggesting that in a model that combines MCL substance and insertion site injury, surgical repair of the MCL and conservative treatment yield similar results. At both 6 and 12 weeks, the V-V rotations of the repaired and nonrepaired knee and structural properties of the repaired and nonrepaired FMTCs (ultimate load, ultimate deformation, energy absorbed, and stiffness) were significantly different from those of the contralateral sham-operated knees ($P < 0.01$ in all cases). However, by 52 weeks, the V-V knee rotation and linear stiffness of the experimental FMTCs were not significantly different from the sham values ($P > 0.1$ in all cases). There was a significant effect of healing time ($p < 0.01$) on these properties. At 12 and

52 weeks postoperatively, all experimental specimens failed in the ligament substance, and the tensile strength and ultimate strain of both the repaired and nonrepaired specimens were significantly less than that of the shams ($p < 0.01$ in all cases).

Future Plans/Implications—The rates of recovery between the ligament substance and the insertion sites were found to be asynchronous as there was a progressive change in failure mode from tibial avulsion at 6 weeks to mid-substance at 52 weeks. The strength of the tibial insertion site increased during the time course of healing while the ligament substance showed little change after the first 12 weeks. A lack of complete recovery of the mechanical properties of the MCL was observed. However, increases in MCL cross-sectional area helped the FMTC to achieve structural properties near to those of the sham control. This suggests that this is a useful model of clinical injury and, therefore, is suitable for the long-term study of grade III MCL injury.

Recent Publications Resulting from This Research

- An Analytical Technique for Defining the Mechanical Properties of Ligament Tissues. Gomez MA, Kwan MK, Woo SL-Y, Joint Biomechanics Symposium at the 3rd Joint ASCE/ASME Mechanics Conference, San Diego, 45-48, 1989.
- Comparison of the Mechanical Properties of the Medial Collateral and Anterior Cruciate Ligaments of the Rabbit Knee. Newton PO et al., Joint Biomechanics Symposium at the 3rd Joint ASCE/ASME Mechanics Conference, San Diego, 53-56, 1989.
- Comparison of Three Methods for Measuring the Cross-Sectional Area Along the Rabbit Medial Collateral Ligament. Danto MI et al., Joint Biomechanics Symposium at the 3rd Joint ASCE/ASME Mechanics Conference, San Diego, 97-100, 1989.
- Effect of Partial and Total Transection of the Anterior Cruciate Ligament on Medial Collateral Ligament Healing in the Canine Knee. Ohland KJ et al., in Transactions of the 35th Annual Orthopedic Research Society, 14:322, 1989.
- The Effects of Age and Sex on the Biomechanical Properties of the Medial Collateral Ligament. Ohland KJ et al., in Transactions of the ASME Winter Annual Meeting, San Francisco, BED 15:113-114, 1989.
- Medial Collateral Ligament Healing Subsequent to Different Treatment Regimens. Gomez MA et al., J Appl Physiol 66(1):245-252, 1989.
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- Effects of Surgical Treatment and Immobilization on the Healing of the Medial Collateral Ligament: A Long-Term Multidisciplinary Study. Inoue M et al., *Conn Tiss Res* 20:1-14, 1990.
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- Improved Methodologies to Differentiate the Mechanical Properties of the Rabbit Anterior Cruciate Ligament (ACL) and Medial Collateral Ligament (MCL). Newton PO et al., in Transactions of the 36th Annual Orthopedic Research Society, 16:509, 1990.
- Long-Term Healing of the Femur-Medial Collateral Ligament-Tibia Complex (FMTC). Weiss JA et al., in Transactions of the First World Congress of Biomechanics, La Jolla, CA, II:292, 1990.
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- Measurement of Changes in Ligament Tension with Knee Motion and Skeletal Maturation. Woo SL-Y et al., *J Biomech Eng* 112:46-51, 1990.
- A New Injury Model to Study Medial Collateral Ligament Healing. Weiss JA et al., in Transactions of the 36th Annual Orthopedic Research Society 15:60, 1990.
- Quantitative Morphology of the Anterior Cruciate and Medial Collateral Ligaments. Hart RA, Newton PO, Woo SL-Y, in Transactions of the 37th Annual Orthopedic Research Society, 16, 1990.
- Aging and Sex Related Changes in the Biomechanical Properties of the Rabbit Medial Collateral Ligament. Woo SL-Y, Ohland KJ, Weiss JA, *Mech Aging Dev* (accepted for publication).
- The Effects of Increased Tension on Healing and Normal Collateral Ligaments. Gomez MA et al., *Am J Sports Med* (accepted for publication).
- The Use of a Laser Micrometer System to Determine the Cross-Sectional Shape and Area of Ligaments: A Comparative Study with Two Existing Methods. Woo SL-Y et al., *J Biomech Eng* (accepted for publication).

Award

The American Orthopedic Society for Sports Medicine 1990 O'Donoghue Sports Injury Research Award.

[312a] Structural and Functional Properties of Normal and Healing Ligaments: Part 2

Purpose—Complete disruption of the medial collateral ligament (MCL) often occurs together with the rupture of the anterior cruciate ligament (ACL) and damage to the medial meniscus—the so called “triad” injury. Using our recently developed model for MCL injury, which included damage of the MCL substance as well as its insertions to bone, we examined MCL healing following a triad injury.

Methodology—In all animals, the MCL was ruptured at the joint line by pulling medially on a 2.5 mm diameter rod passed beneath the ligament. In half the animals, the ACL was then surgically transected and the inner rim ($\cong 50\%$) of the medial meniscus was excised. At 6 and 12 weeks postoperatively, half the animals in each group (isolated MCL rupture and triad injury) were sacrificed, and healing of the MCL was evaluated by comparing the V-V knee rotation, the structural properties of the femur-MCL-tibia complex (FMTC) and the mechanical properties of the MCL substance. The V-V knee rotations of an additional six knees were measured intact and successively following isolated MCL rupture and triad injury.

Results—The animals with a triad injury experienced substantial joint degeneration by 6 weeks. V-V rotations were nearly three times higher for the triad injured knees than for those with isolated MCL rupture ($P < 0.001$) and

remained elevated with time. The ultimate load of the FMTCs of the triad injured knees improved with time ($P < 0.05$), but were only 55% of those with isolated MCL rupture ($P < 0.05$). The modulus of the healing tissue from the triad injured knees was less than half of that of the tissue from the isolated MCL ruptured knees ($P < 0.05$).

Future Plans/Implications—This study demonstrates the deleterious effects of an untreated triad injury on the healing potential of the MCL substance and its insertions. The biomechanical properties of the FMTC and MCL substance imply that the MCL forms a much larger structure following triad injury in an attempt to compensate for its inferior mechanical properties. We have additionally found that after ACL reconstruction, the V-V rotation of the triad injured knees could be restored suggesting that the healing of the MCL may be enhanced by restoring ACL function. We plan to evaluate MCL healing at 6, 12 and 52 weeks following triad injury with ACL reconstruction.

Location Change—The research described herein was performed at the VA Medical Center, San Diego, CA. Dr. Woo transferred to the VA Medical Center, University Drive C, Pittsburgh, PA effective October 1, 1990.

[313] Anterior Cruciate Ligament Healing

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Purpose—Interstitial tears of the anterior cruciate ligament (ACL) do not heal. Studies have focused on the fundamental biological explanation for this deficit. Results with a partial laceration model suggest that simple biomechanical explanations and postulating a "hostile environment" in the synovium are not sufficient to explain the observed healing deficiency. On the basis of original observations, it is proposed that the fibroblast of the ACL is a transitional cell with morphological features similar to the fibrocartilage cell of the meniscus. Ultrastructural studies and immunocytochemical studies with monoclonal antibodies (Mabs) against fibronectin (Fn) show striking differences between the cells of the ACL and the medial collateral ligament (MCL). The ACL lacks the long cytoplasmic processes seen in the MCL and in most other fibrous connective tissue; instead, ACL cells rest in a lacuna-like pool of undifferentiated matrices and partially resemble cartilage cells. It is believed that this morphological appearance may be predictive of the functional response of these cells to injury.

Methodology—A multidisciplinary approach will be used to evaluate and compare the ACL and MCL. State-of-the-art mechanical testing will determine material properties. Molecular and biochemical procedures will assess the metabolic state of these tissues. Scanning electron microscope (EM) studies will be used to define the ligament ultrastructure.

Progress/Results—In a model system of ligament injury, gross healing was defined as complete bridging of the laceration. At the 3- and 7-day time periods, five of the six MCLs were healed; the defect was filled with a translucent "membrane." By 14 days, all lacerations in the MCLs (3/3) were covered by a more hypertrophic ligamentous-like tissue, which seemed to only slightly increase by 28 days.

With the exception of one bridged laceration at 14 days, the lacerations in the ACLs did not heal. The sharp edges created at the time of surgery were rounded off.

Results demonstrate that procollagen messenger (mRNA) levels in MCL tissue are higher than ACL under normal conditions, and increase in response to injury.

The differences in the procollagen mRNA levels of MCL and ACL may reflect the synthesis of collagen in these tissues, and may contribute to differences in their healing capacities.

The stress-strain relationship of each ligament was determined. To achieve a uniform stress distribution during uniaxial tensile testing, the ACL was divided into medial and lateral portions. The mechanical properties of these two portions of the ACL were found to be identical. However, the tangent modulus for the ACL (420 ± 70 MPa) was nearly 50% that of the MCL (810 ± 70 MPa), indicating that the MCL is composed of an intrinsically stiffer material. The tensile strength of the MCL was nearly twice that of the ACL. The strain at failure was similar for the two ligaments. Scanning EM studies showed that the ACL was composed of collagen fascicles with a large amount of endotenon between fascicles. The collagen fibers of the MCL were arranged much more compactly without prominent fascicular divisions.

Future Plans/Implications—The current models and approaches will be extended to provide more detailed information. Hyaluronan and growth factors (including those known to be successful in skin wound healing) will be incorporated to modify the healing response. It is encouraging that recent studies show meniscus healing to be facilitated by fibrin clot, which contains a variety of growth factors able to stimulate chemotaxis, mitogenesis, and/or protein synthesis. Some of this work will be accomplished in cell culture explants from rabbit knee ligament studies.

Recent Publications Resulting from This Research

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- Medial Collateral Ligament Healing Subsequent to Different Treatment Regimens. Gomez MA et al., J Appl Physiol 66(1):245-252, 1989.
- The Early Effect of High Molecular Weight Hyaluronan (Hyaluronic Acid) on Anterior Cruciate Ligament Healing: An Experimental Study in Rabbits. Wiig ME et al., J Orthop Res 8(3):425-434, 1990.
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